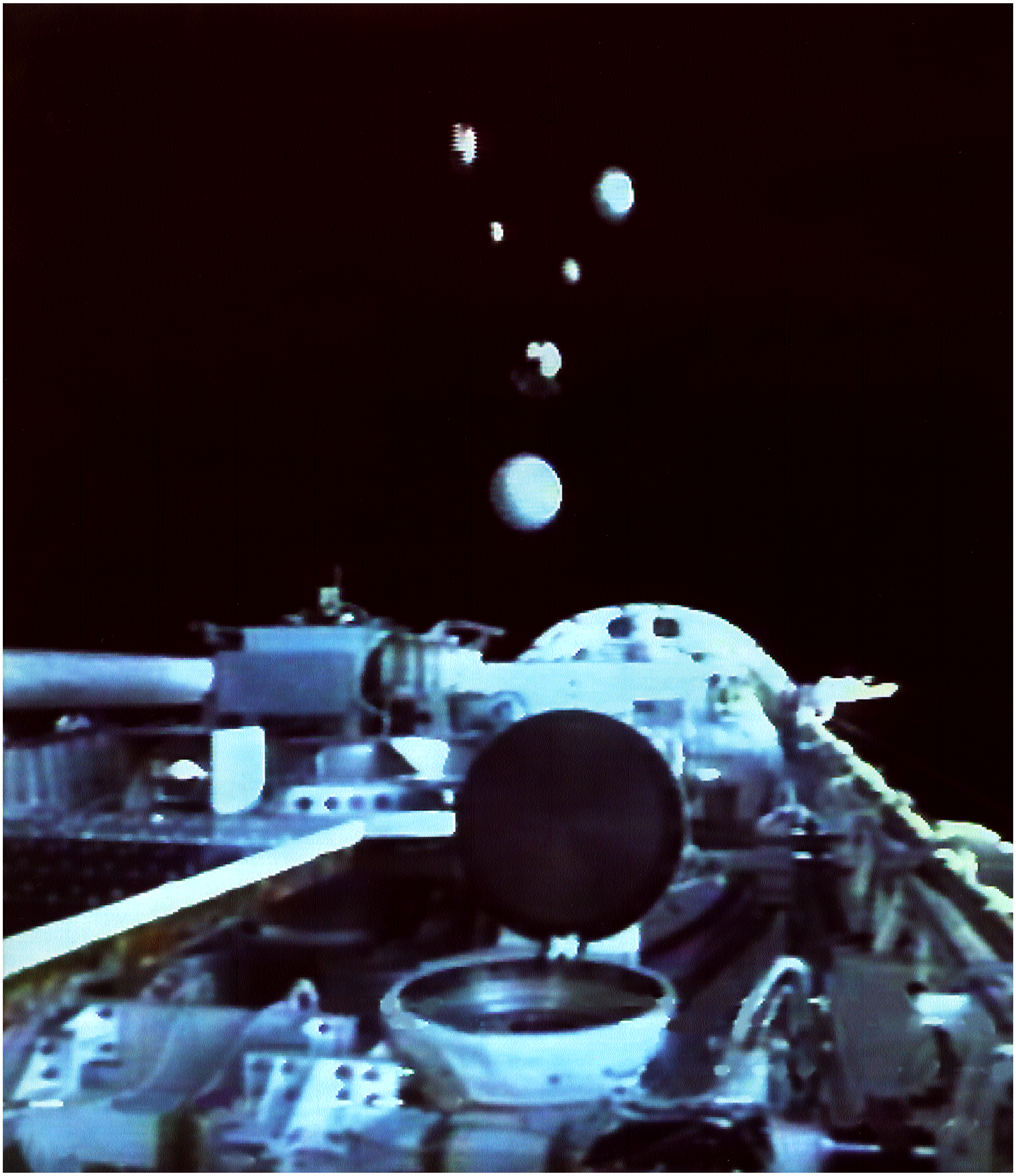


The purpose of the Orbital Debris Calibration Spheres (ODERACS) experiment was to calibrate the radars and telescopes used for orbital debris measurements by putting objects of the size of interest into orbit for observation. One of the pair was polished, the other diffuse. The three pairs were two, four and six inches in diameter. The illustration is a composite of the deployment of the spheres from the Shuttle payload bay.

Chapter 2: Trends and Implications

I. Trends

A. Launch Activity

For the first 25 years of human involvement in space, only the U.S. and the former Soviet Union launched significant numbers of spacecraft. Currently, the seven countries listed in Table 5 have launched objects into Earth orbit. During the past 10 years, there has been a decline in government launches and an increase in commercial launch activity. This trend is expected to continue. In the next decade, additional countries are expected to develop the capability to launch satellites. The launch rates for the seven leading launching nations over the past 11 years is illustrated in Table 5.

Past space activity at most altitudes has placed debris in orbit faster than the natural effect of drag removes it. As a result, the cataloged population of orbital debris increased by about 200 to 300 objects per year, on average, during a time when launch rates were fairly constant. The effect of high solar activity may be seen in the decline in cataloged objects during the late ’70s and the early ’90s (fig. 7).

B. Debris Modeling

In order to project the future debris environment, assumptions have to be made concerning debris sources and sinks. With regard to debris sources, assumptions have to be made concerning launch and fragmentation rates. Uncertainties arise from traffic model predictability, observational limitations, unmodeled sources, limitations of breakup models, debris propagation and lifetime models, and variability in solar activity. Another challenge involves modeling the propagation of a class of objects that are apparently anomalous. This subset of debris is subject to poorly modeled orbital perturbations. The associated problems with their detectability and their ability to be accurately maintained in the catalog influence collision avoidance operations.

Both the DOD and NASA have different types of debris models for a variety of applications. The NASA models can be classified fundamentally into two types: research models and engineering models. The research models use traffic models, atmospheric density models, and satellite fragmentation models to predict the current and future debris environment. The research models are tested and calibrated by data obtained from measurements from laboratory experiments and measurements of the environment. The results of the research models and measurements are then synthesized into a simplified model which can easily be used by the engineering community.

Atmospheric models are derived from the orbital decay characteristics of known objects as well as density measurements. Since the geophysical indices driving these models do not parameterize the atmospheric density very well, the atmospheric drag cannot be modeled accurately; however, the atmosphere represents a small uncertainty in orbital debris models. A significantly larger uncertainty results from the breakup models which describe not only the number and size of fragments produced from a satellite breakup, but their new orbits and the object’s susceptibility to atmospheric drag. These models are based on a limited number of ground tests, and represent the largest uncertainty in debris research models.

Table 5. Worldwide Launches

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
U.S.	18	18	22	22	17	6	8	12	18	27	18	28	23	27
Russia	98	101	98	97	97	91	95	90	74	75	59	54	47	49
Japan	3	1	3	3	2	2	3	2	2	3	2	1	1	2
ESA	2	0	2	4	3	2	2	7	7	5	8	7	7	8
India	1	0	1	0	0	0	0	0	0	0	0	1	0	2
China	1	1	1	3	1	2	2	4	0	5	1	4	1	5
Israel	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Total	123	121	127	129	120	103	110	117	101	117	88	95	79	93

The DOD has developed and enhanced a variety of predictive models in support of debris research dealing with the generation and propagation of orbital debris resulting from the breakup of space assets. These models range in purpose from modeling the breakup of space assets to modeling the population of the LEO debris environment. The models also range in complexity from personal computer-based empirical models to workstation and super computer-based theoretical models. Empirical breakup models describe the mass and velocity distributions of the debris resulting from the breakup (explosion or hypervelocity collision) of space assets. A theoretical model is used to predict the physical response of satellites and satellite components to explosions and hypervelocity impacts.

For space debris environment modeling, the DOD borrowed the framework of the NASA research model EVOLVE and made several modifications. One significant change was to replace the empirical breakup model in EVOLVE with DOD empirical breakup model called IMPACT. Other modifications dealt with making the code more efficient and user-friendly.

NASA favors use of an orbital debris engineering model which has been in use since 1990.[47] This model is currently being tested against measurements made since 1990, and while there are some differences between the measurements and the model predictions, the differences are not yet considered significant enough to update the model.

The engineering model makes the following assumptions about future space activities:

(1) Launch activity will continue at the same average rate it has for the last 10 years, allowing payloads and upper stages placed into orbit to continue to accumulate at the same rate. This assumption is assessed to be conservative because it does not postulate significant new space-based activities (cf p. 19 re LEO constellations).
(2) Future solar cycles will resemble the average of all past recorded cycles.
(3) Future operational practices will minimize (but not eliminate) the possibility of explosions in orbit.

Using these assumptions, European Space Agency (ESA), NASA, and Russian models predict an increasing probability of orbital collisions over time. These orbital collisions would cause the small debris particles generated by these hypervelocity impacts to increase at a faster rate than predicted by launch and explosion rates alone.

C. Debris Generation Projections

The major source of both large and small debris in LEO has been fragmentation of satellites and rocket bodies. This process has produced more large, trackable debris than has space operations, and much more small untrackable debris. The launching of a payload into space from a booster or upper stage generates orbital debris composed of spent rocket stages, clamps, covers, etc., but does not produce much untrackable debris in LEO. More recent designs and practices eliminate or retain these devices so that they do not become debris.

There are very large uncertainties involved with predicting future debris environments. Making these predictions requires estimates of future debris sources and sinks. This includes estimates of future world launch activity (when, how much mass on orbit, what orbit), estimates of future on-orbit explosions (when, where, what, and how many), estimates of on-orbit collisions (when, where, what, and how many), estimates of future solar cycle activity, and estimates of mitigation strategies and their effect on the debris environment. Another aspect of future predictions that is not modeled by NASA or DOD is the impact of future technology and its effect on reducing the hazard of debris to operational assets.

Because of these uncertainties, DOD does not consider the possibility of future random collisions as a debris source in its orbital debris predictions. DOD considers the concept of random collisions one that requires further validation before it should be incorporated into its models. The results of the DOD analysis at altitudes of 400 and 800 km for the cumulative debris population larger than 1 cm are shown in Figure 11. Imbedded in this DOD projection of the future orbital debris environment are trends in debris growth due to launch activity, breakup events, and solar activity.

Historically, the major energy source for satellite fragmentations has been the stored energy in upper stage propellant, batteries, or pressure containers. In the short term, these energy sources are responsible for the near-term environment of small debris.

In the long term, several models predict that chance collisions could be an important source of satellite fragmentation unless current design and operation practices are modified at some time in the future. Figure 12 illustrates this using a NASA research computer model to predict the future 1 cm orbital debris environment in low Earth orbit using three different operational practices.

All three cases assume the past launch rate of approximately 100 launches per year. Case 1 is the

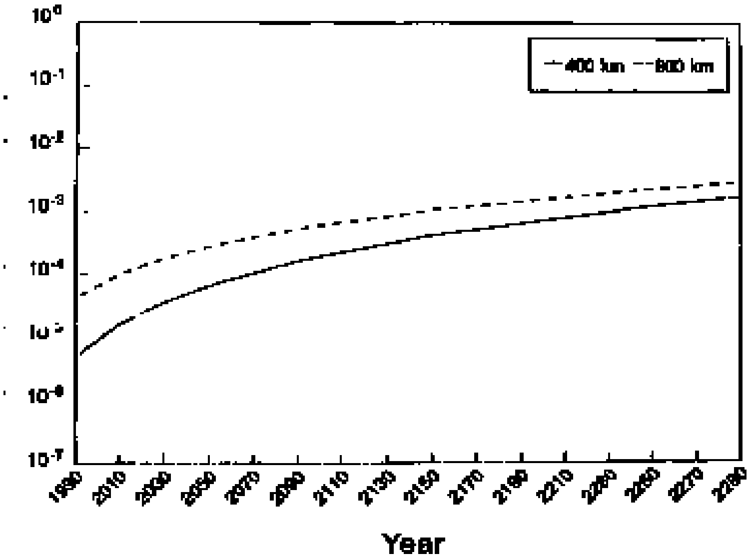


Figure 11. The Expected Future Orbital Debris Environment

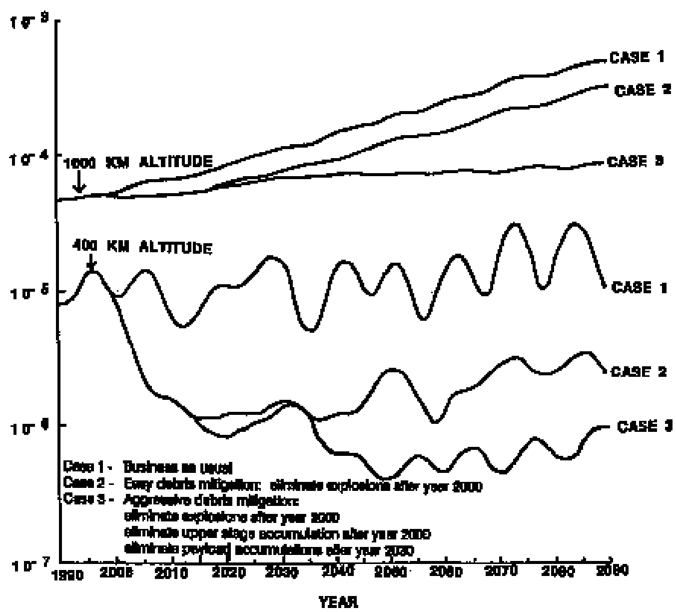


Figure 12. EVOLVE Projections of Future Debris Environment as a Function of Different Future Operations Scenarios

"business as usual" case, where objects are allowed to explode at the same rate they have in the past. Case 2 represents the "easily achieved mitigation" technique of preventing future explosions after the year 2000. Although eliminating explosions produces a short-term reduction in the rate of accumulation of small debris, this action alone does not significantly alter the long-term projection, especially at the higher altitudes of LEO. This is because the NASA model predicts that fragments from random collisions between larger objects become the major source of small debris. Case 3 represents the more "aggressive debris mitigation" of requiring future payloads and rocket bodies to not remain in orbit at the end of their operational life. This reduces the rate of random collisions, and consequently reduces the rate of growth in small debris. Even so, in the long term, this model still predicts a slow increase in the small orbital debris population. ESA independently developed models provide essentially identical results.[54]

It is important to point out that predicting the future debris environment is not intended to be an exact extrapolation to the "true" debris particle density. The predictions presented here are intended to provide an indication of an expected fragment environment for particular initial conditions and assumptions. In this case, the following conditions would exist:

(1) Collisional breakup of space objects may become a source for additional orbital debris in the near future.

(2) Over a longer period of time, the orbital debris environment is likely to increase with time, even though a zero net input rate may be maintained. Ultimately, this could lead to an environment increasingly controlled by collisions and difficult to alter.

The discussion in the preceding paragraphs has been limited to LEO. The situation is considerably different in GEO. There are currently about 920 cataloged objects that traverse GEO altitudes, of which only about 150 are geostationary. The others are in either geosynchronous transfer or semi-synchronous, highly elliptical (“Molniya”) orbits. The average spatial density of objects is 2 to 3 orders of magnitude less than in LEO. Low densities combines with low average relative velocities make the current likelihood of a collision insignificant. Thus the near-term concern for debris in GEO is less compelling than for LEO.

II. Implications

The probability of collision is mainly a function of the spacecraft size, the orbital altitude, and the period of time that the spacecraft will remain in orbit. The orbital debris environment in LEO could present a problem even now for space operations which involve large spacecraft in orbit for long periods of time. A space station is the primary example of a large spacecraft, and it will be necessary to shield large areas of it to achieve the design safety criteria.

The “design driver” is the determination of an acceptable level of risk. For example, the specified level of risk of manned space programs from Apollo to the present varied from .01 to .05 probability of penetration over the lifetime of the space system. The actual level of risk experienced by these spacecraft has been significantly less than that specified because other design requirements made the spacecraft more robust. The earlier manned space programs addressed only the natural meteoroid environment, but the proposed Space Station requirement addresses both the natural meteoroid and the orbital debris environments. Substantial growth of the debris environment may also require additional shielding for smaller unmanned satellites.

A. Operational Experience of Orbital Debris Effects on Spacecraft

While there has been no documented case of a spacecraft failure due to an orbital debris impact, there are a number of spacecraft failures for which the cause is unknown. The breakup of Kosmos 1275 is one such failure where an orbital debris impact is the prime suspect. Kosmos 1275 broke up for no apparent reason not long after it was inserted into orbit. An orbital debris impact was suspected because the size and velocity distribution of the fragments following the breakup were characteristic of a collisional fragmentation.[59]

Direct evidence of small orbital debris impacts has been gained from examination of surfaces brought back from orbit by the Space Shuttle. The exterior surfaces of the Orbiter show many impact pits after each mission. Pitting of the Orbiter windows results in replacement of a window every other mission, on average. Similar effects are found on other surfaces returned from space. The largest such area in space for the longest time was the LDEF that was in orbit for 69 months. Its surface was covered with tens of thousands of impact pits, the largest being about 0.63 cm in diameter. Laboratory studies of the pitted surfaces confirm that about half the larger impacts where the source could be identified were caused by debris, while practically all of the smallest impacts were man-made aluminum oxide debris.[58]

We expect to see similar small debris impact effects on the Mir space station. Russia has reported very little direct information on the debris damage to Mir. Informally, we have learned that Mir suffered pitting effects similar to those seen by the U.S. during Space Shuttle missions. The Russians are also reported to have found it necessary to replace Mir’s window covers and to shield its exterior light bulbs due to damage from orbital debris. Russia has reported exposing witness plates on Mir; however, these plates have not been completely analyzed. As part of the U.S. Shuttle flights to the Mir station, NASA plans to conduct a photo survey of the Mir in an attempt to quantify and characterize any damage from orbital debris.

Often asked is the question why there has not been a major impact damage observed on LDEF or Mir. Calculations of the probabilities of a damaging collision for LDEF and Mir which take into account the area of these spacecraft, their operational altitude, and their time on orbit predict a low probability of a damaging collision. The observational data is consistent with these calculations.

Figure 13 illustrates the expected impact rate on a typical LEO spacecraft. Because of the relatively modest size of such spacecraft the expected impact frequency is low and that much of the spacecraft is not vulnerable to impact damage e.g., solar arrays. It is worthwhile to note that at these altitudes the man-made environment exceeds the meteoroid environment at all sizes.

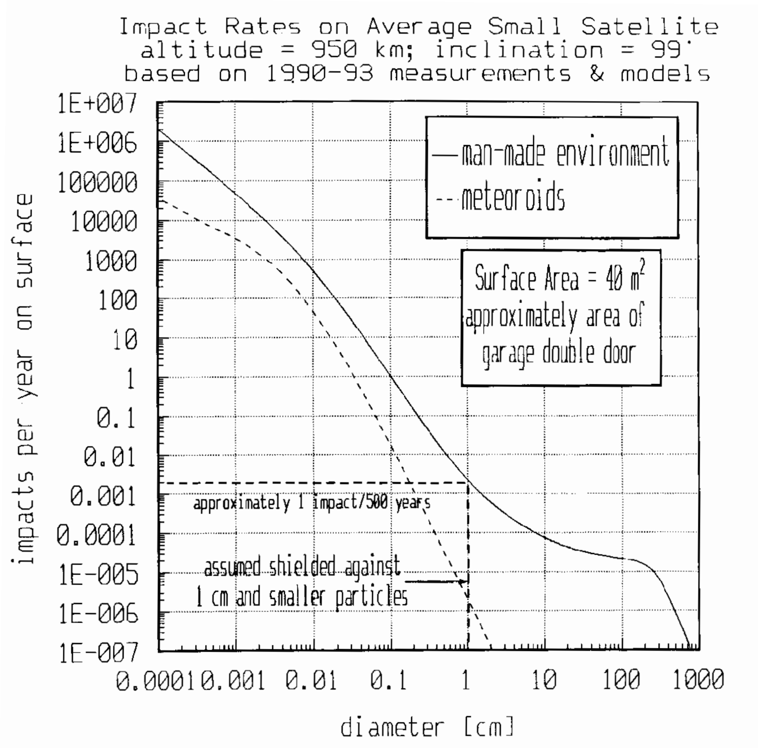


Figure 13. Orbital Debris and Meteoroid Impacts on a Small Satellite at 950 km, 1994-2030

B. Future Operations

Space Station and Extravehicular Activity (EVA) Considerations

The implication of orbital debris growth is important to all aspects of human space flight. Even though the final design of the International Space Station (ISS) is still evolving, it is possible to draw some early conclusions on the effects of orbital debris on the design. Figure 14 illustrates some of the factors that are involved in performing the Space Station orbital debris risk assessment. This assessment is based upon an ISS design with a 5000 square meter exposed surface area, a 400 km operating altitude, and 51.6 degrees inclination.

The ISS is being designed to protect critical areas against the highest probability particles of 1.4 cm and smaller which accounts for 99.8% of the debris population. The analysis shown in Figure 14 predicts the chance of a 1.0 cm or larger object impacting the Space Station in one possibility in 71 years. However, debris larger than 1.4 cm striking the Space Station will not necessarily cause a catastrophic problem.

Impacts with objects too small to cause a penetration or significant structural damage will be the most frequent. Most impacting particles will be in the size range of grains of sand. These very small impacts will cause surface degradation on sensitive surfaces such as optical surfaces and solar panels. This type of damage has been planned for and will be repaired during routine maintenance operations.

As noted, the ISS has been designed to shield for the highest probability impacting particles. However, for protection against a collision with very large debris objects, the ISS will employ an improved version of the type of collision avoidance measures that are now routinely utilized to protect the Space Shuttle and the Mir.

In addition to the measures already discussed, a number of other measures that are currently being pursued are:

1. Proven "hatch position protocols" will be employed to give additional protection within the crew quarters.
2. Internal structures such as equipment racks will be utilized to provide crew protection from a debris impact. Other devices such as spall blankets are being considered and tested.
3. Various Space Station repair methods in work.
4. Modified operational procedures during periods of high flux (i.e., meteor storms).
5. And finally, in the event that the future orbital debris environment is more severe than currently forecast, the Space Station is being designed to accommodate additional debris shields that can be delivered and deployed after the Space Station is operational.

Another very important consideration is EVA since crew members are more directly exposed to the debris environment. The risk is a function of the duration of exposure and the capability of the EVA suit to resist impact events. Presently the risk is small due to small exposed area of the EVA suit and the short duration of exposure.

Potential Effect of LEO Satellite Constellations on the Environment

The advent of large LEO satellite constellations could present a significant new issue for the orbital debris environment. Table 6 lists the proposals that have been put forward as candidates for frequency allocation by U.S. companies and others. In each case, the numbers of satellites shown are the total for the operational configuration of the constellation. The numbers of planes in which the spacecraft are deployed varies widely. Design life ranges from 5 to 10 years. Additional replacement satellites must be launched to replace failed units or those that have reached end of life.

The inclination and altitude bands for these systems places most of them in what are already the most heavily used regions of LEO. Adding the large numbers and cross section characteristic of these constellations increases the probability of collisional damage particularly because the high inclination leads to high spatial density over the poles.

Table 6. Some Proposed LEO Constellations

System	Number of Spacecraft	Altitude (Kilometers)	Inclination
Teledesic	840	700	98.2
Iridium	66	780	86.0
Globalstar	48	1400	47.0
Odyssey	12	10360	55.0
Aries	48	1020	90.00
Ellipsat	24	500-1250	63.5
Vita	2	800	99.0
Orbcom	18	970	40.0
Starsys	24	1340	50-60

While it is uncertain how many of these systems will be deployed, at least three have mature technical definition and a significant fraction of the required financing. An analysis was performed

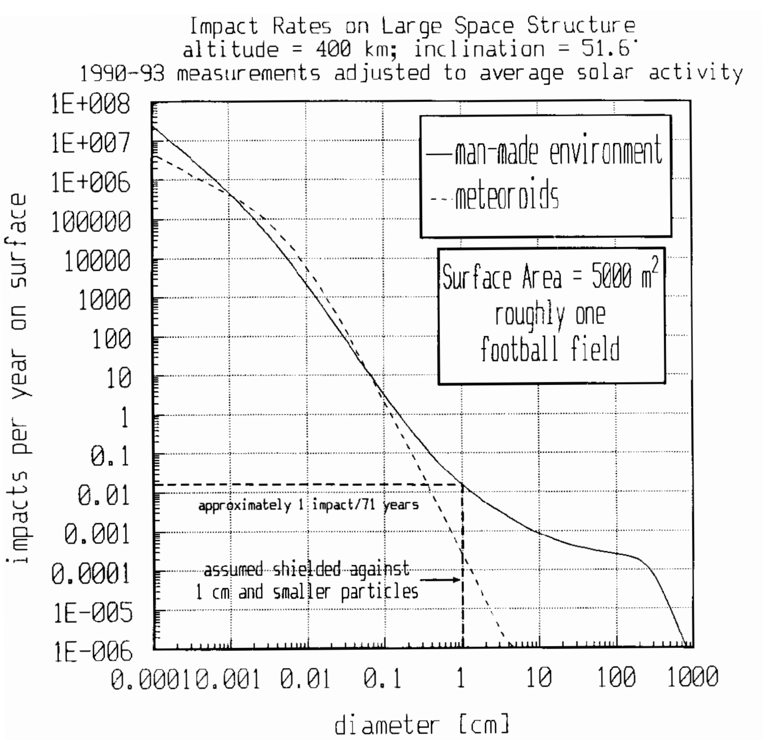


Figure 14. Orbital Debris and Meteoroid Impacts on a Large Space Station at 400 km, 1994-2030

using the EVOLVE model to assess the effect of deploying three of the systems. The analysis assumed that five launches a year would deploy multiple spacecraft and examined the effect of such an increase in LEO activity and the influence of a spectrum of mitigation strategies in the long-term future environment. Mitigation options ranged from actions to eliminate future explosions to removing upper stages and spacecraft from orbit at the end of mission lifetime. As the curves in Figure 15 indicate, failure to take any action will lead to significant increase in orbital debris during the next century, but relatively modest active measures (as identified in cases 3 and 5) can keep the environment essentially as it is today. Teledesic and Iridium both plan to deorbit their upper stages and spacecraft at their end of life.

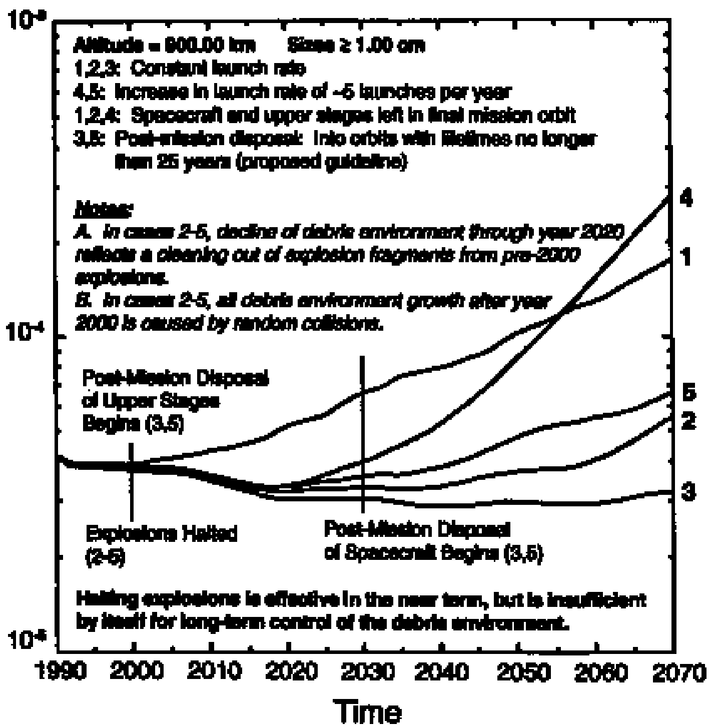
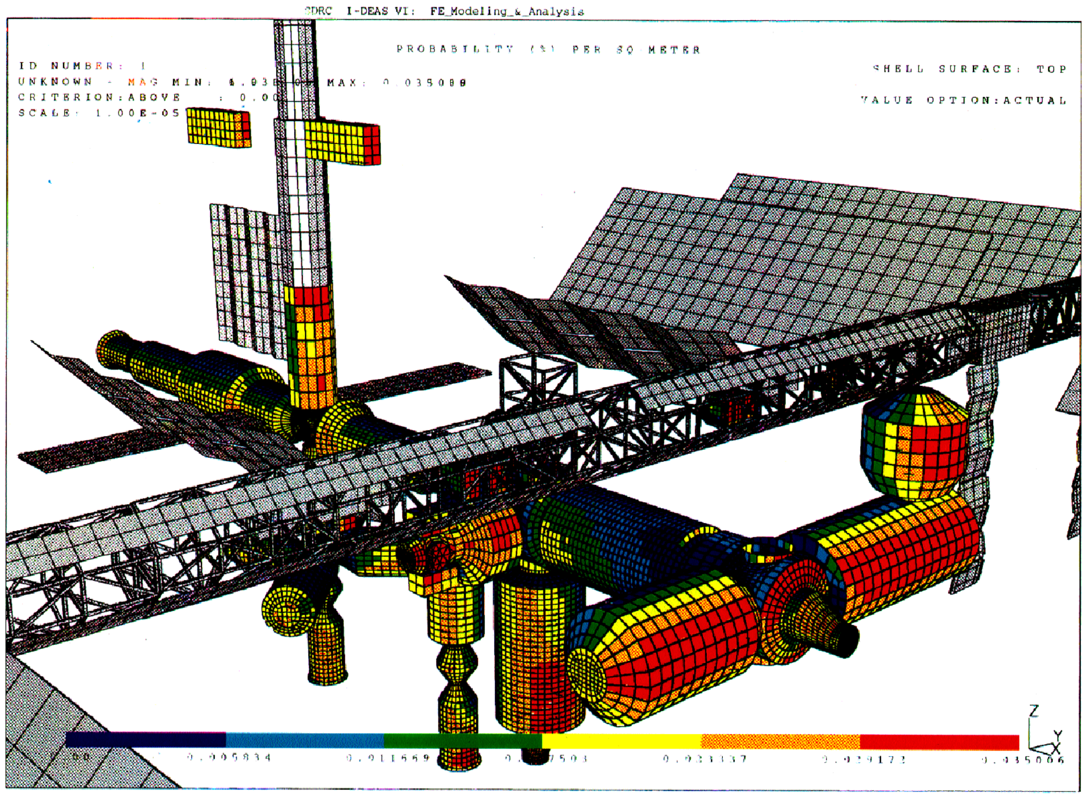
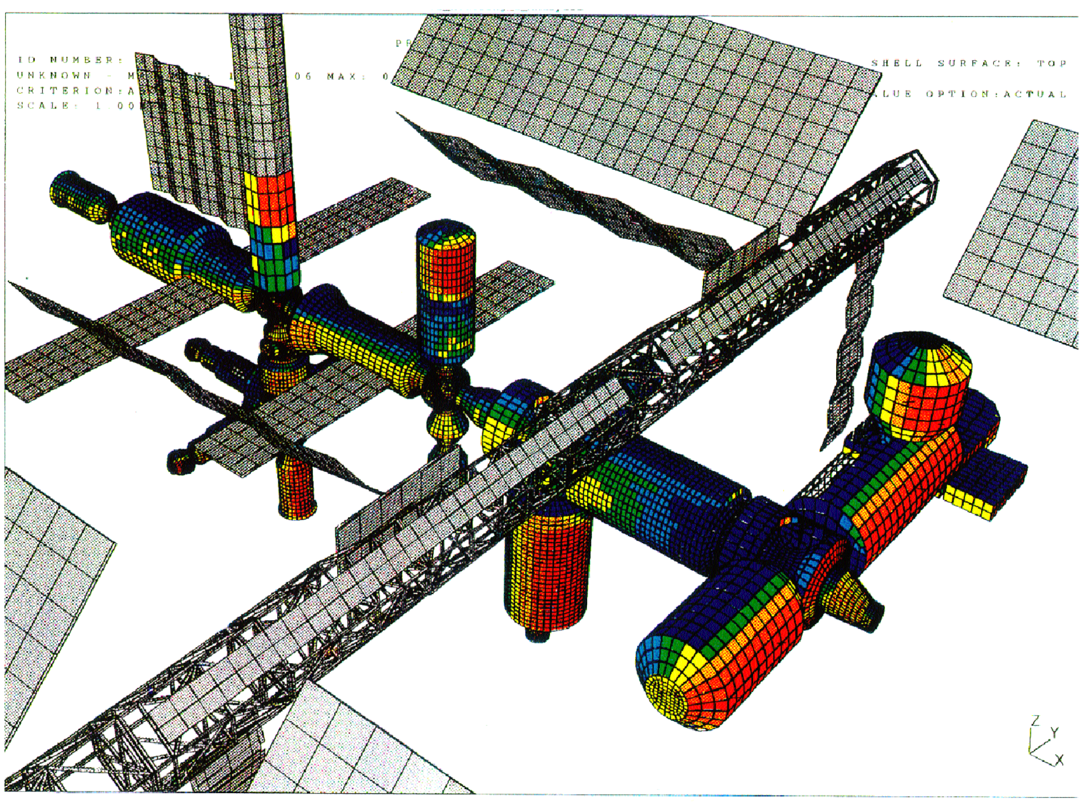
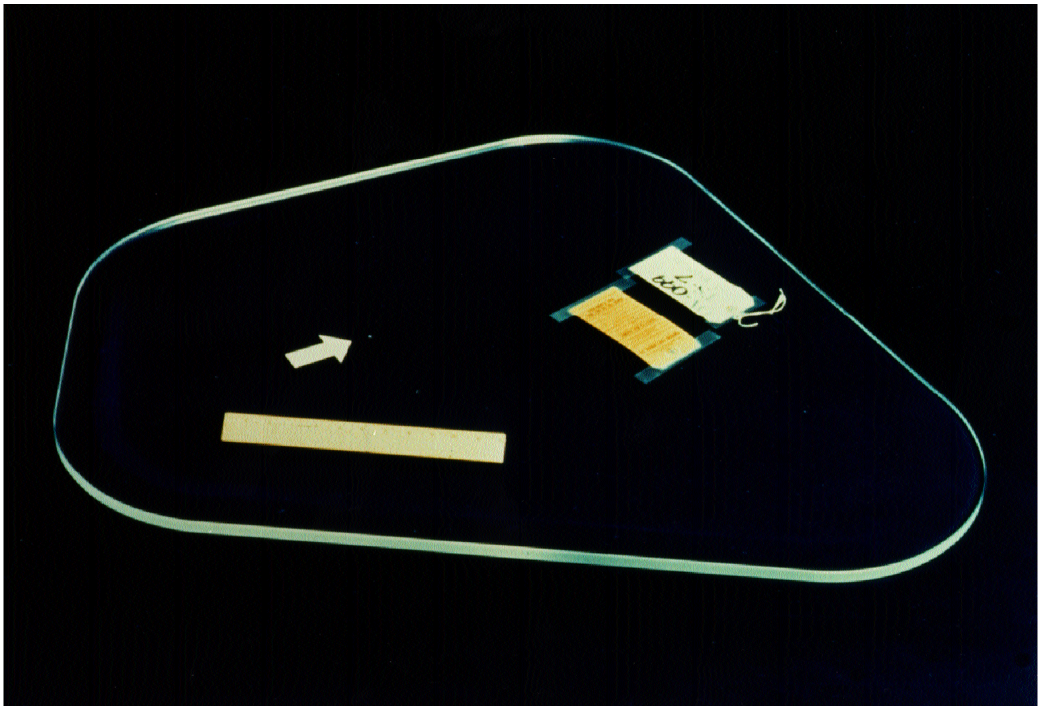


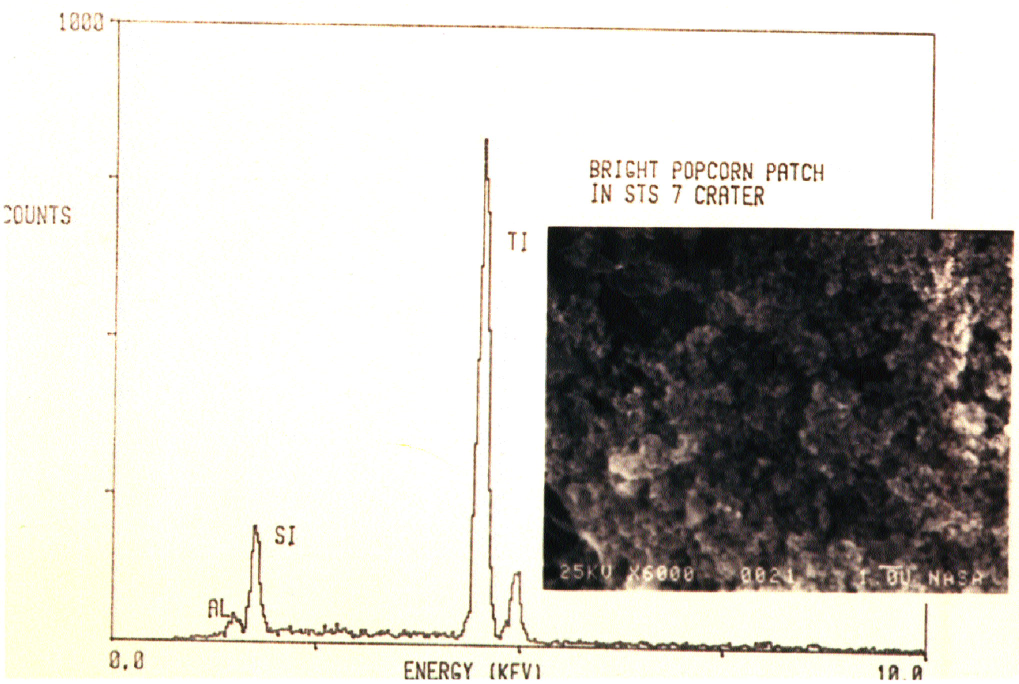
Figure 15. EVOLVE Projection of the Future Environment With Increased Launch and Spacecraft Operation in LEO





NASA uses BUMPER computer code to determine risks of meteoroid and orbital debris impact damage and critical penetration for a number of spacecraft such as the Space Station (shown in figure). BUMPER is also used to determine the most likely areas of the spacecraft to be impacted which can then be designed with more shielding protection. For instance, the forward and side areas of the Space Station will be exposed to the highest concentration of the orbital debris impacts as indicated by the red and orange colors in this figure. These areas of the Space Station will be designed with the heaviest shielding to increase the protection to crew and critical equipment from meteoroid/orbital debris impact.





During the 70 flights the Space Shuttle has flown, it—like the LDEF has been hit many times by debris in orbit. Generally, these impact events cannot be observed post-flight because the surface is heated during entry and the evidence is lost. The Shuttle windows and radiator panels on the interior of the payload bay doors, however, do experience impacts and preserve the evidence. This window from the flight of STS-7 experienced an impact event and was subsequently analyzed.

The scanning electron microscope response illustrates that the crater is characterized by the titanium dioxide pigment characteristic of spacecraft thermal control paints and the aluminum silicate binder used to adhere the paint to the spacecraft structure.

There have been 60 windows replaced on the Orbiter over 70 flights because of hypervelocity impacts. The craters are caused by objects the size of a grain of salt moving at 8 to 10 km/second. The window replaced is not part of the crew pressure vessel but an external window provided to protect the two pressure windows. The window is replaced because, on the next launch, the flaw could cause it to fail due to aerodynamic loads.